535162

Detecting a Terrestrial Biosphere Sink for Carbon Dioxide: Interannual Ecosystem Modeling for the Mid-1980s

Christopher S. Potter * and Steven A. Klooster †

* Ecosystem Science, NASA-Ames Research Center,
Mail Stop 242-4, Moffett Field, CA 94035

† California State University Monterey Bay
Seaside, CA 93955

Date: April 3, 1998

* Contact corresponding author at
tel. 650-604-6164; fax 650-604-4680
email cpotter@gaia.arc.nasa.gov

Abstract. There is considerable uncertainty as to whether interannual variability in climate and terrestrial ecosystem production is sufficient to explain observed variation in atmospheric carbon content over the past 20-30 years. In this paper, we investigated the response of net CO_2 exchange in terrestrial ecosystems to interannual climate variability (1983 to 1988) using global satellite observations as drivers for the NASA-CASA (Carnegie-Ames-Stanford Approach) simulation model. This computer model of net ecosystem production (NEP) is calibrated for interannual simulations driven by monthly satellite vegetation index data (NDVI) from the NOAA Advanced Very High Resolution Radiometer (AVHRR) at 1 degree spatial resolution. Major results from NASA-CASA simulations suggest that from 1985 to 1988, the northern middle-latitude zone (between 30 and 60 degrees N) was the principal region driving progressive annual increases in global net primary production (NPP; i.e., the terrestrial biosphere sink for carbon). The average annual increase in NPP over this predominantly northern forest zone was on the order of +0.4 Pg (10^{15} g) C per year. This increase resulted mainly from notable expansion of the growing season for plant carbon fixation toward the zonal latitude extremes, a pattern uniquely demonstrated in our regional visualization results. A net biosphere source flux of CO_2 in 1983-1984, coinciding with an El Niño event, was followed by a major recovery of global NEP in 1985 which lasted through 1987 as a net carbon sink of between 0.4 and 2.6 Pg C per year. Analysis of model controls on NPP and soil heterotrophic CO_2 fluxes (R_h) suggests that regional warming in northern forests can enhance ecosystem production significantly. In seasonally dry tropical zones, periodic drought and temperature drying effects may carry over with at least a two-year lag time to adversely impact ecosystem production. These yearly patterns in our model-predicted NEP are consistent in magnitude with the estimated exchange of CO_2 by the terrestrial biosphere with the atmosphere, as determined by previous isotopic ($\delta^{13}C$) deconvolution analysis. Ecosystem simulation results can help further target locations where net carbon sink fluxes have occurred in the past or may be verified in subsequent field studies.

Introduction

Terrestrial biosphere response to interannual variability in climate may explain a significant portion of year-to-year variation in atmospheric carbon content observed over the past two decades (Keeling et al., 1989; Ciais et al., 1995; Keeling et al., 1996). It is plausible that terrestrial ecosystems introduce delay and damping mechanisms into the global carbon cycle that are detectable in the atmospheric CO_2 record. As evidence, fluctuations in atmospheric CO_2 associated with El Niño events appear to have lagged variations in surface air temperatures by one or two years (Keeling et al., 1995). However, there is a lack of direct evidence from field measurements to attribute these fluctuations with certainty to interannual variability in terrestrial ecosystem production.

Satellite observations of vegetation greenness have been used to monitor the duration of the active growing season for terrestrial vegetation during the 1980s (Myneni et al., 1997). Longer growing seasons are apparent, particularly in areas of the northern high latitudes (between 45° N and 70° N), where notable warming has occurred in the spring. These satellite observations appear to be consistent with an increase in amplitude of the seasonal cycle of atmospheric CO_2 since the early 1970s.

Nevertheless, greenness estimates from remote sensing data need to be combined with estimated controllers of ecosystem carbon fluxes in order to quantitatively assess how actual net CO_2 exchange has responded to fluctuations in climate (Running and Hunt, 1993; Goward and Prince, 1995). Ecosystem carbon models can take into account moisture stress and soil biogeochemical processes that may not be detected by satellite observations of vegetation greenness. The present study involves the global application of one such ecosystem carbon model that uses monthly 1° satellite data to drive net terrestrial production estimates and process-level algorithms for soil CO_2 fluxes.

The NASA Ames ecosystem model version (Potter and Klooster, 1997) of CASA (Carnegie-Ames-Stanford Approach) has been calibrated for non-equilibrium state simulations driven by satellite vegetation index data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) over the years 1983-88, in an effort to capture some of the intrinsic ecosystem regulation of plant production and soil respiration by biophysical processes and interannual responses to anomalous events.

Methods

To make a direct assessment of terrestrial ecosystem exchange of carbon, we simulated global net primary production (NPP) and soil heterotrophic respiration (R_h) for the years 1983-1988 using the NASA-CASA Biosphere model version (Potter and Klooster, 1997). As a unique feature of CASA, model predictions of NPP and R_h have been validated previously against measured seasonal oscillations of atmospheric carbon dioxide (Potter et al., 1993; Denning; 1994), and against multi-year estimates of NPP from field stations and tree rings (Malmström et al., 1997).

The model is driven with a satellite greenness index from the NOAA Advanced Very High Resolution Radiometer (AVHRR). Calculation of monthly interannual NPP at all ice-free terrestrial grid cells is based on the concept of light-use efficiency. NPP is a product of cloud-corrected solar irradiance (S), fractional intercepted photosynthetically active radiation (FPAR) and a maximum light use efficiency term (ε), modified by temperature (T) and moisture (W) stress scalars.

$$NPP = S \ FPAR \ \varepsilon \ T \ W \qquad (1)$$

In the global or regional simulation mode, estimation of FPAR comes from a vegetation index derived from AVHRR FAS-NDVI data (Sellers et al., 1994), whereas the ε term derives from calibration to previous field estimates of NPP. The T stress term is computed with reference to an AVHRR-derivation of optimal temperatures (Topt) for plant production (Potter et al., 1993). The T_{opt} setting ranges from near 0° C in the Arctic to the middle thirties in low latitude deserts.

Soil carbon cycling and R_h flux components of the NASA-CASA model (Figure 1) are based on a compartmental structure comparable to the mechanistic CENTURY ecosystem model (Parton et al., 1992). First-order equations simulate loss of CO_2 from decomposing plant residue (metabolic and structural fractions of NPP) and microbes at the soil surface. Near-surface soil organic matter (SOM) pools are presumed to vary in carbon residence time and chemical composition. Active (microbial biomass and labile substrates), slow (chemically protected), and passive (physically protected) fractions of the SOM are represented.

Monthly 1° climate anomalies for air surface temperature and precipitation (Dai and Fung, 1993), together with long-term (30-year) mean values (Leemans and Cramer, 1990) and surface solar irradiance (Bishop and Rossow, 1991), were used to generate model drivers for the period 1983-1988. Dai and Fung (1993) used, among other sources, the World Surface Station Climatology at NCAR.

Model FPAR is derived using the Normalized Difference Vegetation Index (NDVI) from AVHRR (Sellers et al., 1994). The period 1983-1988 was used to eliminate the potential effects of satellite change-over and major volcanic eruptions. The monthly 1° FAS-NDVI product (Los et al. 1994) includes Fourier smoothing algorithms (FA) and solar zenith (S) angle corrections to remove anomalous signals from the global NDVI data sets. Our calibrated global value (Potter et al., 1993) of ε based on these climate and FAS-NDVI products is 0.57 g C MJ^{-1} PAR.

Complete AVHRR data sets for the 1980's have been produced from NOAA Global Area Coverage (GAC) Level 1B data, and consist of reflectances and brightness temperatures derived from the five-channel cross-track scanning AVHRR aboard the NOAA Polar Orbiter 'afternoon' satellites (NOAA-7, -9, and -11). Monthly composite NDVI data sets are designed to remove much of the contamination due to cloud cover present in the daily AVHRR data sets (Holben, 1986). To generate a composite data set, eight to eleven consecutive days of data are combined, taking the observation for each 5- to 8-km bin from the date with the highest NDVI value. Only data within 42 degree of nadir are used in the composite to minimize spatial distortion and bi-directional effect biases at the edge of a scan. A Rayleigh correction is calculated and applied using a standard radiative transfer equation and methodology, which follows the work of Gordon et al. (1988).

As part of the Global Inventory Monitoring and Modeling Studies (GIMMS) program (Los et al., 1994) of NASA Goddard Space Flight Center, Sellers et al. (1994) describe Fourier smoothing algorithms (FA) and solar zenith (S) angle corrections for interannual AVHRR data sets to further remove anomalous NDVI signals from global 1° data sets (averaged from 8-km values) for the 1980's. The FA correction is intended to remove remaining cloud cover or aerosol interference. Settings for this FA correction include three temporal harmonics and a weighted Fourier transform, i.e. values which fall above the Fourier curve are given more weight than values below the curve. This assumes that higher NDVI values are more likely to be correct than low NDVI values which could occur during periods of cloud or smoke formation. FAS processing appears to eliminate artifactual problems present in other NDVI data sets. Specifically, FAS(IR) NDVI data sets have been shown to reproduce multi-year yield data and tree ring growth patterns from field studies world-wide (Malmström et al., 1997); the FAS(IR) NDVI data show minimal correlations with equatorial crossing times of the NOAA satellites, which suggests correction for orbital drifts and switches between satellites (e.g., NOAA 9 to NOAA 11).

FAS-NDVI data sets (scaled in units from 0 to 1000) for 1983-88 (Los et al., 1994) were made available for the present study. Unlike in earlier versions of the CASA-Biosphere model (Potter et al., 1993; Potter and Klooster, 1997), we avoided use in this NASA-CASA version of AVHRR-NDVI data sets with interpolation and reconstruction (IR) features added (Sellers et al., 1994). The main justification for this decision is based on lack of verification of the NDVI reconstruction algorithm for the extent of tropical evergreen forest.

To accommodate interannual variability in model drivers, we developed a protocol to initialize soil pools (water and carbon) with states that realistically represent near-term climate and vegetation greenness conditions preceding the 1983-88 time frame. The mean surface temperature over 1980-1982 (Dai and Fung, 1993) and the 30-year mean values for precipitation (Leemans and Cramer, 1990), along with mean monthly FAS-NDVI and solar irradiance from 1980s time series data sets, were found to most closely represent initialization drivers for the model to a near steady-state over a computational period of 300 years. We tested alternative driver combinations, but found that: (1) surface temperatures must reflect recent warming trends to produce near steady-state conditions for soil carbon (SLOW pool; Figure 1) typical for the late 1970s-early 1980s; (2) rainfall varies considerably from year-to-year, which justifies use of a long-term mean; and (3) NDVI data does not exist for the late 1970s-early 1980s, which justify use of a mean of existing data for the mid-1980s.

The initial "near steady-state" pool sizes for water and modern carbon storage were used to start the interannual simulation run in the transient mode from 1983-1988 using actual (anomaly adjusted) monthly climate and FAS-NDVI drivers for this time period. Model state variables were allowed to change from month to month without the constraint of an equilibrium between NPP, litterfall transfer to the soil, heterotrophic soil CO_2 fluxes, or soil carbon turnover and storage.

Results and Discussion

Our global model results identify several large regions as having experienced substantial interannual variability in NPP sink fluxes of carbon between 1984-88. In areas of Canada, Europe, and Russia, NPP increased from 1985-88 (Figure 2a). This is mainly as a result of warmer than long-term average spring temperatures and lower summer drought stress which promoted a northward expansion of plant production over the period (Figure 2b). Across the entire African Sahel, and in eastern and southern Africa and eastern Brazil, annual NPP showed a strong recovery from the severe drought effects of the 1983 El Niño event (Keeling et al., 1995). In areas of the north-central United States, North Africa, and Australia, mean estimated NPP decreased chiefly as a result of periodic shortages in precipitation. These model responses are the result of combined effects of NDVI and climate anomalies. Our regional analyses suggest that interannual fluctuations in the satellite greenness signal account for 30-80% of the variability in predicted NPP, with climate anomalies accounting for the remaining variability (also see analysis in Potter et al., submitted). This finding of NDVI accounting for more than 50% of the variation in modeled NPP is also consistent with the results of Malmström et al. (1997), who made interannual comparisons of CASA model predictions with agricultural yield data from sites around the world.

The time series trend in predicted global CO_2 flux from the NASA-CASA model suggests that terrestrial ecosystem production was a net source for carbon in 1983 and 1984. Predicted NEP shifted to become a biosphere sink for carbon starting in 1985 at 2.6 Pg C yr^{-1} and continued, albeit at a diminishing rate, through 1988 (Figure 3). Higher plant production progressively adds organic material to regional soil pools which, with longer turnover times for carbon than in green vegetation, respond more gradually to warming in terms of CO_2 return to the atmosphere. The zone between 30° N and 60° N accounted for over 20% of the global net sink flux in 1987 and 100% of the carbon sink in 1988. These NASA-CASA results support other accumulated evidence for a substantial terrestrial sink in the Northern Hemisphere (Keeling et al., 1989; Ciais et al., 1995; Melillo et al., 1996)., and help identify specific ecosystem-level processes for this inferred carbon storage.

As a means of independent confirmation of NASA-CASA results, estimation of the terrestrial biosphere flux of carbon from isotopic ($\delta^{13}C$) deconvolution analysis (Keeling et al., 1995) appears most consistent with a net biosphere sink for CO_2 over the middle of the period (i.e., 1985-1987; Figure 3). A six to twelve month offset in peak CO_2 fluxes is evident in comparison of these two estimates. This offset might be explained solely by systematic biases cited in the deconvolution analysis (Keeling et al., 1995). We note furthermore that interannual variability in terrestrial biosphere fluxes of CO_2 from the $\delta^{13}C$ deconvolution model method includes other (non-NEP) sources, such as biomass burning, which can be detected best with high resolution remote sensing (e.g., 30-m Landsat; Peddle et al., 1997). These biomass burning fluxes would help explain differences in the two model results such as those seen in 1983 and 1987. Therefore, net carbon source fluxes are not strictly comparable in the two modeling approaches, a point demonstrated in global ecosystem analyses not driven by satellite data (Kindermann et al., 1996), but which also confirm the magnitude of NASA-CASA estimates.

Four sites were selected to evaluate the model over a wide range of eco-climatic conditions for terrestrial carbon exchange (Figure 4). Net ecosystem production (NEP), defined as NPP-R_h, was used to characterize seasonal carbon exchange with the atmosphere. At all test sites, interannual fluctuation in NEP was mainly a function of variability in NPP fluxes rather than R_h, which is consistent with results from previous global modeling studies of terrestrial ecosystem carbon fluxes (Kindermann et al., 1996). Predicted yearly R_h shows substantially less year-to-year variation (coefficient of variation (CV) < 10%) over this time series than annual NPP (CV ≥ 10%), especially in the semi-arid grassland (West Africa) location, where the model predicts the highest interannual variability (CV > 25%) in NPP fluxes. At the Amazon forest location, fluctuations in R_h track the seasonal patterns of monthly NPP with a lag time of just one to several months. This short lag results from the estimate of a relatively constant year-round supply of freshly deposited leaf material to soil decomposers in humid evergreen forests. Hence, the storage of relatively large pools of slowly decomposing litter and SOM carbon, which carry residence times of 2 to 25 years and generally account for 40-60% of annual R_h fluxes of CO_2 (Potter and Klooster, 1997) apparently buffers the interannual effect of climate variability on R_h and NEP over large areas.

In contrast to the observed lagged effects in the R_h response, above ground fluctuations (10-50% from year-to-year) in mean annual FPAR have a direct and immediate effect on NPP sink fluxes of CO_2. For example, at the northern boreal forest location in Canada, small but notable increases were detected in the 1° NDVI signal early in the growing seasons of 1984, 1985 and 1988. This advanced spring greening is potentially associated with an early disappearance of snow cover, a pattern verified in comparatively high-resolution studies of the NDVI temporal signal over the years from 1981 to 1991 (Myneni et al., 1997). Warmer (than long-term average) air temperatures in the spring months can drive higher estimated plant transpiration and reduced surface water runoff. These changes in hydrology were combined with the observed greening trend in NDVI-FPAR for prediction of higher NPP by the NASA-CASA model. Several weeks of production were added during the early growing season.

In addition, from 1985 to 1987, predicted drought stress during the summer decreased at the northern boreal forest site due to the combined effects of lower evaporative demand and sporadically higher rainfall. This can progressively extend the growing season in terms of NPP fluxes. The model result of 30-50% higher annual NPP over the years 1985-88 (relative to the "reference" year 1984, during which global climate anomalies were lowest) leads to the prediction of positive annual NEP at the middle- and high-latitude zones, typically in the range of +30 to +60 g C m^{-2} yr^{-1}. These positive NEP values are the result of a small difference between two relatively large numbers (NPP and R_h). However, each of these model predictions is qualitatively consistent with reported interannual controls on net ecosystem carbon exchange measured in tower studies of temperate forest sites (Goulden et al., 1996).

Under warmer low-latitude (< 20° N or S) conditions, seasonal moisture deficits were seen to severely restrict monthly NPP at the western African location selected to represent semi-arid grasslands. The NDVI responded fairly strongly to interannual patterns of monthly rainfall, although predicted increases in peak seasonal greenness tended to lag positive precipitation anomalies by about a year (Figure 4; also see Potter et al., 1997). At the much wetter tropical forest location in the Amazon Basin (near Manaus), seasonal low NPP mainly showed the effects of notable rainfall deficits during the El Niño events of 1983 and 1987. Low rainfall in the Amazon reduces NDVI-FPAR estimates. Predicted soil R_h in the tropical moist forest location is less sensitive to these relatively severe drought events than NPP.

In summary, we hypothesize that use of the satellite greenness index together with medium-term (decade long) climate fluctuations captures the most important responses of terrestrial ecosystems to interannual variability in biosphere-atmosphere exchange of CO_2. Analysis of NASA-CASA modeled map results (e.g., Figure 2a) can also locate new validation studies for net carbon sinks at the ecosystem scale. The spatial detail made possible through the use of satellite remote sensing data in ecosystem modeling uniquely facilitates this type of region-by-region, year-by-year assessment of potential C sinks.

Although the theoretical basis for NDVI as a key land surface parameter related to plant carbon fixation has been spelled out previously in some detail (Running et al., 1996), much work remains with respect to combining optical remote sensing with radiative transfer modeling to enhance the accuracy of FPAR and leaf area index (LAI) estimates at scales from regional to global Assumptions and algorithms must be improved concerning leaf angle distribution, basic leaf optical properties, and clumping of canopy components as a means to generate the improved relationships among satellite vegetation indices, LAI, and FPAR (Myneni et al., 1995). With improved algorithms in hand, a new generation of NASA Earth Observing System (EOS) platforms should provide decades of well-calibrated surface NDVI data for monitoring seasonal and interannual variability in terrestrial carbon sinks over regional to global scales (USGCRP, 1997).

Results from this ecosystem modeling study, along with other studies that have used satellite observations to infer plant production, should be qualified nonetheless to point out that, while estimates may be indicative of interannual response of terrestrial carbon flux to variability in climate, their conclusions cannot be extrapolated directly to infer either relatively short-term (day-to-day) or long-term (several decades) response of the biosphere to global warming. The processes of ecosystem acclimation to higher surface temperatures, changes in daily surface hydrology, disturbances (e.g., fires), land use, and elevated atmospheric CO_2 levels must be included in subsequent modeling analyses that include potential geographic shifts occurring over several decades in plant functional types, physiological responses, and soil carbon turnover rates. The mechanisms controlling terrestrial NEP may interact differently under varying conditions of large-scale climate oscillation (i.e., changes in frequency and amplitude). The NDVI driver alone, while it has been proven useful as an indicator of potential past changes in plant greenness (Myneni et al., 1997), is not adequate to capture actual production changes of this extent and magnitude. Second-order soil contributions and feedbacks in lagged systems responses also require greater understanding and complementary modeling approaches.

ACKNOWLEDGMENTS. The authors thank J. Coughlan, D. Peterson, R. Nemani and one anonymous reader for review of the manuscript in earlier stages of preparation. This research was supported by the NASA Ames Research Center Basic Research Council. Recent refinement of the soil carbon model was supported by NASA Headquarters Program in Ecological Processes and Modeling Branch, Office of Earth Science. We credit the Numerical Aerodynamic Simulation facility at NASA Ames Research Center for computing support, and the High Performance

Computing and Communications Program for access to their testbed computers. Thanks to T. Whorf for providing atmospheric carbon data, S. Los for providing FAS-NDVI maps, A. Dai and I. Fung for providing gridded climate anomaly data sets, and V. Brooks for analysis support.

References

Bishop, J. K. B., and W. B. Rossow, Spatial and temporal variability of global surface solar irradiance, *J. Geophys. Res.*, *96*, 16,839-16,858, 1991.

Ciais, P., Tans, P. P., White, J. W. C., Trolier, M., Francey, R. J., Berry, J. A., Randall, D. R., Sellers, P. J., Collatz, J. G. and Schimel, D. S. 1995. Partitioning of ocean and land uptake of CO_2 as inferred by $\delta^{13}C$ measurements from the NOAA/CMDL global air sampling network. *J. Geophys. Res.*, 100, 5051-5057.

Dai, A. and I. Y. Fung, 1993, Can climate variability contribute to the missing CO_2 sink? *Global Biogeochemical Cycles.*, **7**, 599-609.

DeFries, R. and J. Townshend, 1994, NDVI-derived land cover classification at global scales. *International Journal of Remote Sensing*, **15**, 3567-3586.

Denning, A. S. *Investigations of the Transport, Sources, and Sinks of Atmospheric CO_2 using a General Circulation Model* (Atmos. Sci. Pap. 564, Colorado State University, Fort Collins, CO, 1994).

Goulden, M. J., J. W. Munger, S.-M. Fan, B. C. Daube, and S. C. Wofsy. 1996. Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. *Science.* 271:1576-1577.

Goward, S. N. and S. D. Prince, 1995, Transient effects of climate on vegetation dynamics: satellite observations, *Journal of Biogeography*, **22**, 549-563.

Keeling, C. D., Bacastow, R. B., Carter, A. F., Piper, S. C., Whorf, T. P., Heimann, M., Mook, W. G., & Roeloffzen, H., *Aspects of Climate Variability in the Pacific and Western America.* Peterson, D. H. et al., Eds. (American Geophysical Union ,Washington, DC, 1989), pp. 165-236.

Keeling, C. D., T. P. Whorf, M. Whalen, and J. van der Plicht. 1995. Interannual extremes in the rise of atmospheric carbon dioxide since 1980. *Nature.* 375:666-667.

Keeling, C. D., Chin, J. F. S., Whorf, T. P., Increased activity of northern vegetation inferred from atmospheric CO_2 measurements, *Nature*, 382, 146-149, 1996

Kindermann, J., G. Würth; and G. H. Kohlmaier. 1996. Interannual variation of carbon exchange fluxes in terrestrial ecosystems. *Global Biogeochemical Cycles.* 10:737-755.

Leemans, R. and W. P. Cramer, 1990, The IIASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid. WP-41. International Institute for Applied Systems Analysis, Laxenburg Working Paper, IIASA, Laxenberg, Austria, 60 pp.

Los, S. O., C. O. Justice, and C. J. Tucker, 1994, A global 1x1 NDVI data set for climate studies derived from the GIMMS continental NDVI data. *International Journal of Remote Sensing*, **15**, 3493-3518.

Melillo, J. M., Prentice, C., Farquhar, G., Schulze, E.-D. & Sala, O. *IPCC Second Scientific Assessment of Climate Change*. Houghton, J. T. et al., Eds. (Cambridge Univ. Press, Cambridge, 1996), pp.455-483.

Myneni, R. B., Maggion, S., Iaquinta, J., Privette, J. L., Gobron, N., Pinty, B., Verstraete, M. M., Kimes, D. S., and D. L. Williams. 1995. Optical remote sensing of vegetation: Modelling, caveats and algorithms. Remote Sens. Environ., 51: 169-188.

Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar and R. R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, 386, 698-674.

Parton, W. J., McKeown, B., Kirchner, V., Ojima, D. *CENTURY Users Manual*. (Colorado State University, Fort Collins, 1992).

Peddle, D. R., F. G. Hall, E. F. LeDrew, D. E. Knapp. 1997. Classification of forest land cover in BOREAS. II: Comparison of results from a sub-pixel scale physical modeling approach and a training based method. *Canadian Journal of Remote Sensing*. 23: 131-142 .

Potter, C. S., J. Randerson, C. B. Field, P. A. Matson, P. M. Vitousek, H. A. Mooney, and S. A. Klooster, Terrestrial Ecosystem Production: A Process Model Based On Global Satellite And Surface Data, *Global Biogeochem. Cycles*, *7*, 811-841, 1993.

Potter C. S. and S. A. Klooster. 1997. Global model estimates of carbon and nitrogen storage in litter and soil pools: Response to change in vegetation quality and biomass allocation. *Tellus*. 48B(1):1-17.

Potter, C. S., Klooster, S. A., & Brooks, V. *Interannual Biosphere-Atmosphere Variability* (NASA Workshop, Tucson, Arizona, 1997).

Potter, C. S., S. A. Klooster, and V. Brooks. Interannual variability in terrestrial net primary production: Exploration of trends and controls on regional to global scales. *J. Geophys. Res.* (Submitted).

Running, S. W. & Hunt, E. R. Jr. *Scaling Ecological Process Leaf to Globe* . Ehleringer, J. R. & Field, C. B., Eds. (Academic Press, San Diego, 1993), pp. 141-158.

Running, S. W., R. B. Myneni, R. R. Nemani, and J. Glassy. 1996. MOD15 LAI/FPAR Algorithm Theoretical Basis Document. NASA Headquarters, Washington, DC.

Sellers, P. J., C. J. Tucker, G. J. Collatz, S. O. Los, C. O. Justice, D. A. Dazlich, and D. A. Randall, 1994, A global 1x1 NDVI data set for climate studies. Part 2: the generation of global fields of terrestrial biophysical parameters from the NDVI, *International Journal of Remote Sensing*, **15**, 3519-3545.

U.S. Global Change Research Program (USGCRP). 1997. *Our Changing Planet*. Committee on Environment and Natural Resources Research of the National Science and Technology Council. Washington, D.C.

Fig. 1. NASA-CASA soil sub-model. Litter and soil C and N transformations lead to substrates for trace gas production. Carbon pools are outlined in black and labeled with C-to-N ratios, C fluxes in solid arrows, CO_2 production in stippled arrows; Nitrogen pools in gray, N fluxes in gray arrows. Litter, microbe (MIC) and soil organic (SLOW and OLD) pools are shown. Structural (S) and metabolic (M) pools are shown for leaf and root litter.

Fig. 2. Interannual results from the NASA-CASA model. a. Global map of mean terrestrial net primary production (NPP) over 1985-88, normalized by predicted NPP for the "reference" year 1984. Yellow-red in the northern hemisphere temperate and high latitude zones indicate potential areas of carbon sink flux in response to warmer than long-term average spring temperatures and lower summer drought stress. Red in areas of the African Sahel and eastern Brazil indicate a recovery of annual NPP from the severe drought effects of the 1983 El Niño event. Areas in white indicate no detectable plant production or missing data. b. Predicted monthly pattern of NPP within the northern latitude zones over the model years 1985-1988, relative to the model 1984 NPP estimate. Higher peak seasonal production and the northward expansion of the growing season are evident over these years in comparison to 1984, during which annual NEP was close to zero for the region. Seasons are defined according to the months January, April, July, and October (J, A, J, O).

Fig. 3. NASA-CASA model estimate (solid line) of global ecosystem carbon exchange with the atmosphere, compared to terrestrial biosphere flux of carbon recomputed from isotopic ($\delta^{13}C$) deconvolution data (Keeling et al., 1995; dashed line). Running 12-month totals are plotted. Positive yearly mean values represent a net source flux from the biosphere to the atmosphere, whereas negative yearly values represent a net sink flux into the biosphere from the atmosphere.

Fig. 4. Monthly model predictions for selected ecosystem sites. The top panels show estimated FPAR (dark solid line, unitless left vertical axis) and surface solar irradiance (dashed line, W m^{-2} on right vertical axis). The middle panels present estimated stress scalars for moisture (solid line, unitless) and temperature (dashed line, unitless); a value of one represents the lowest level of stress on NPP. The bottom panels show NPP (solid line) and R_h (dashed line), both as positive flux values in g C m^{-2}. The initial model state is labeled as "INIT". Ecosystem type definitions (DeFries and Townshend, 1994) and geographic site locations are: northern boreal forest, 56° N 126° W; temperate grassland, 53° N 9° E; semi-arid grassland, 16° N 12° W; tropical moist forest, 2° S 59° W.

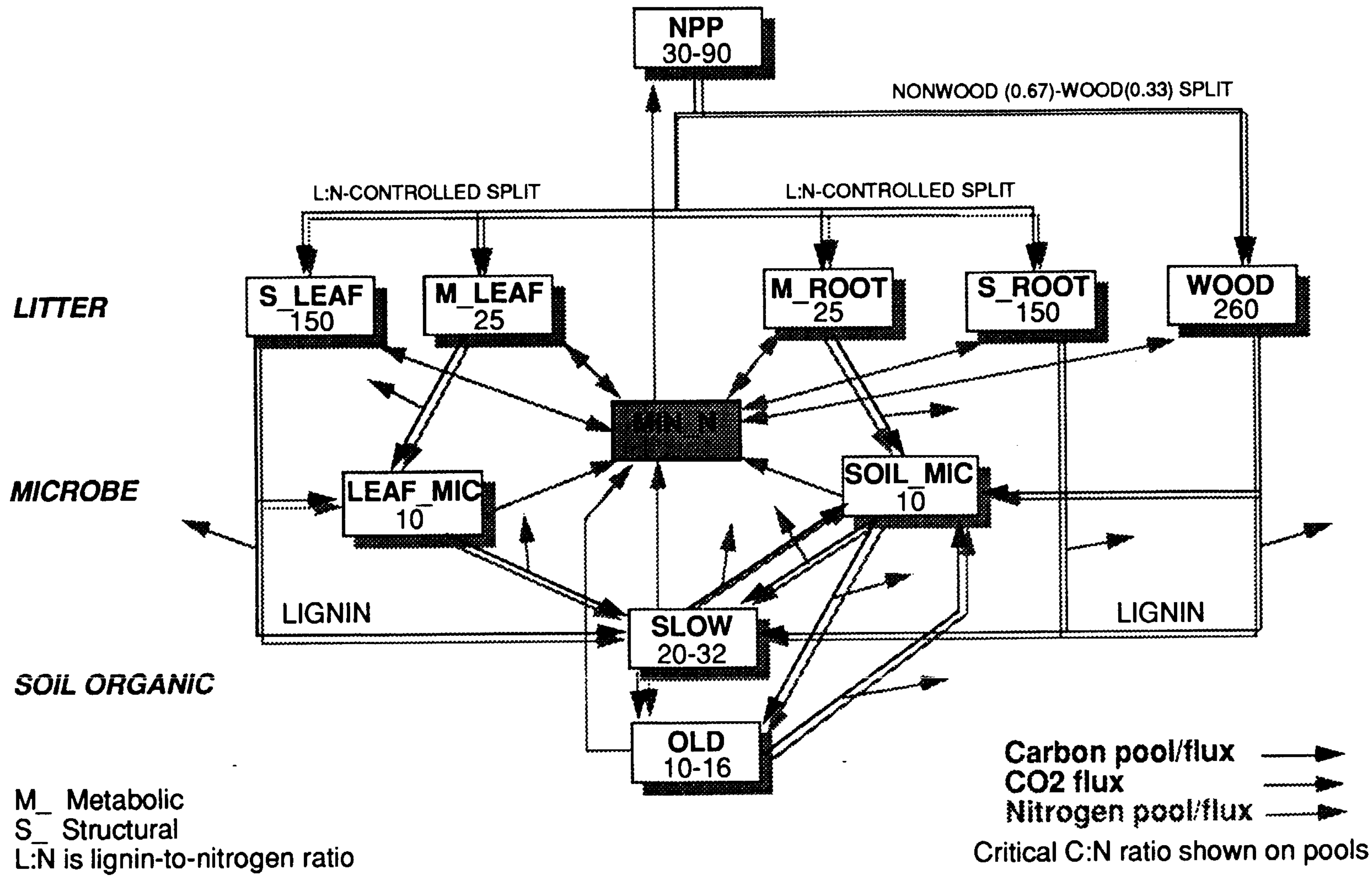
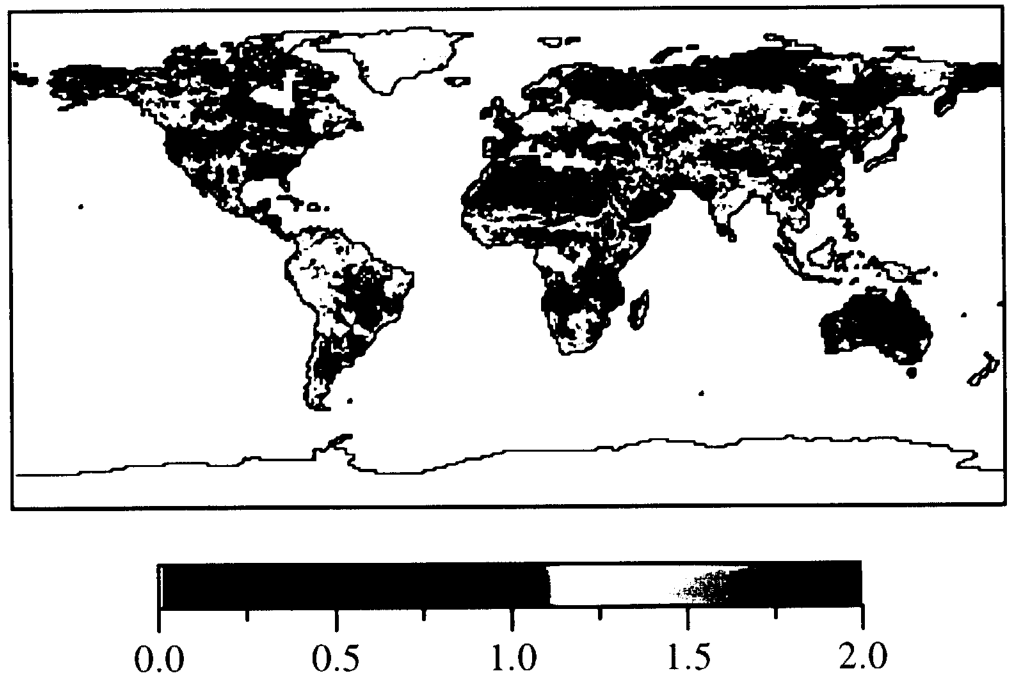

NPP
30-90
NONWOOD (0.67)-WOOD(0.33) SPLIT
L:N-CONTROLLED SPLIT
L:N-CONTROLLED SPLIT
LITTER
S_LEAF
150
M_LEAF
25
M_ROOT
25
S_ROOT
150
WOOD
260
MIN_N
MICROBE
LEAF_MIC
10
SOIL_MIC
10
LIGNIN
LIGNIN
SOIL ORGANIC
SLOW
20-32
OLD
10-16
M_ Metabolic
S_ Structural
L:N is lignin-to-nitrogen ratio
Carbon pool/flux
CO2 flux
Nitrogen pool/flux
Critical C:N ratio shown on pools

Fig. 2

a.


0.0
0.5
1.0
1.5
2.0

b.

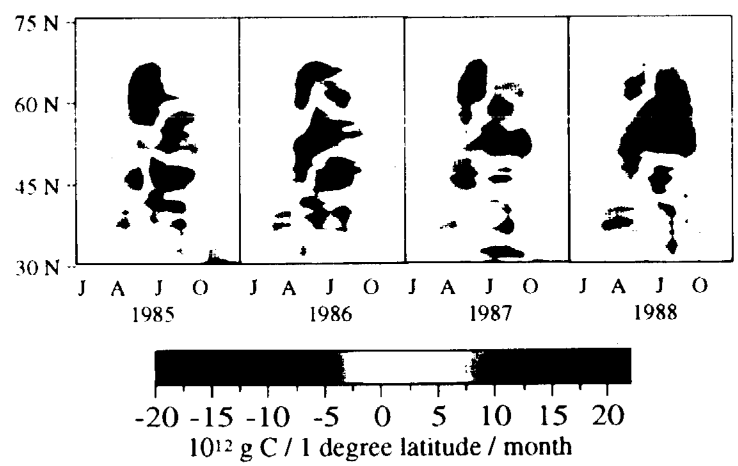

75 N
60 N
45 N
30 N
J A J O
1985
J A J O
1986
J A J O
1987
J A J O
1988
-20 -15 -10 -5 0 5 10 15 20
10^12 g C / 1 degree latitude / month

Fig. 3

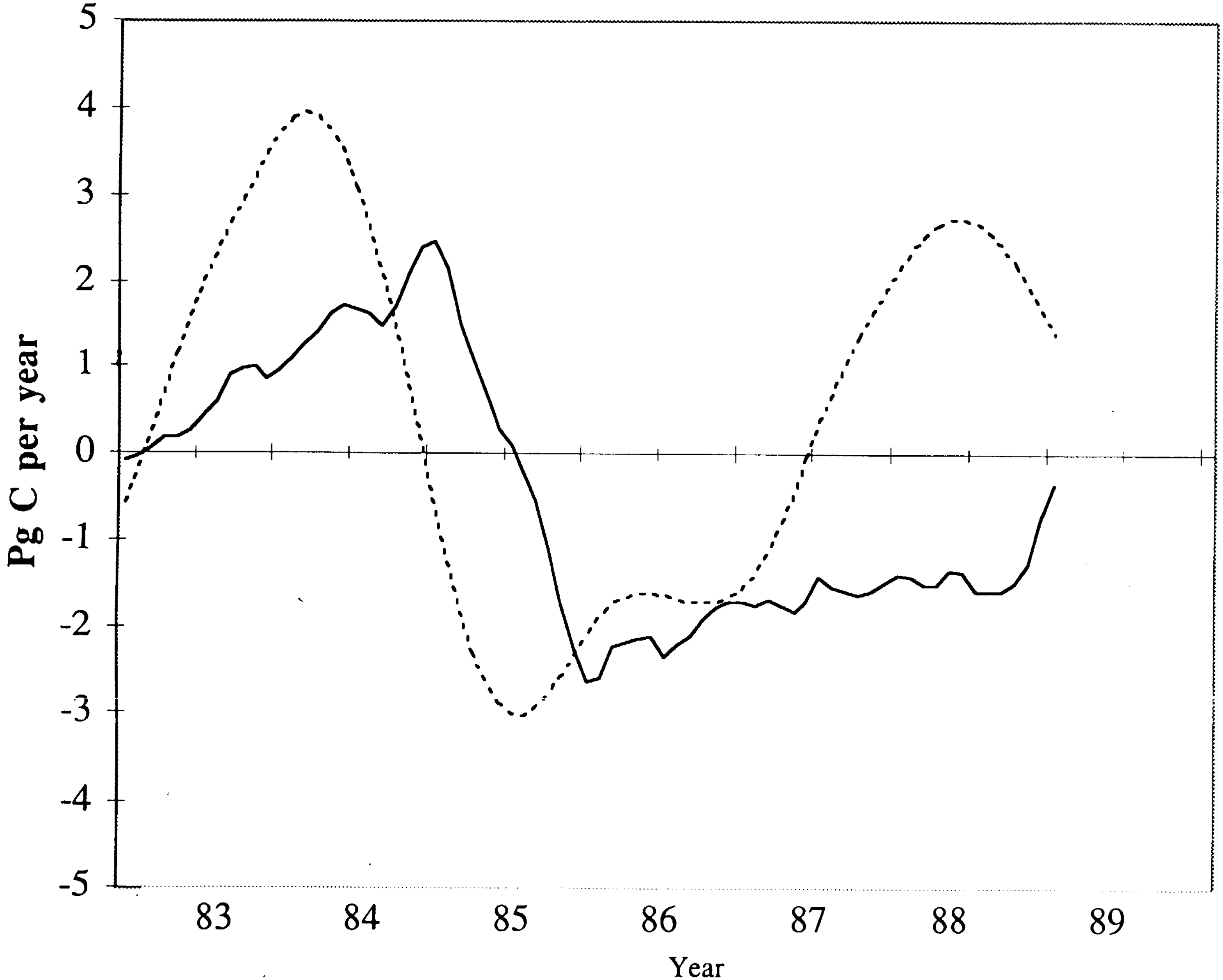


Fig. 4

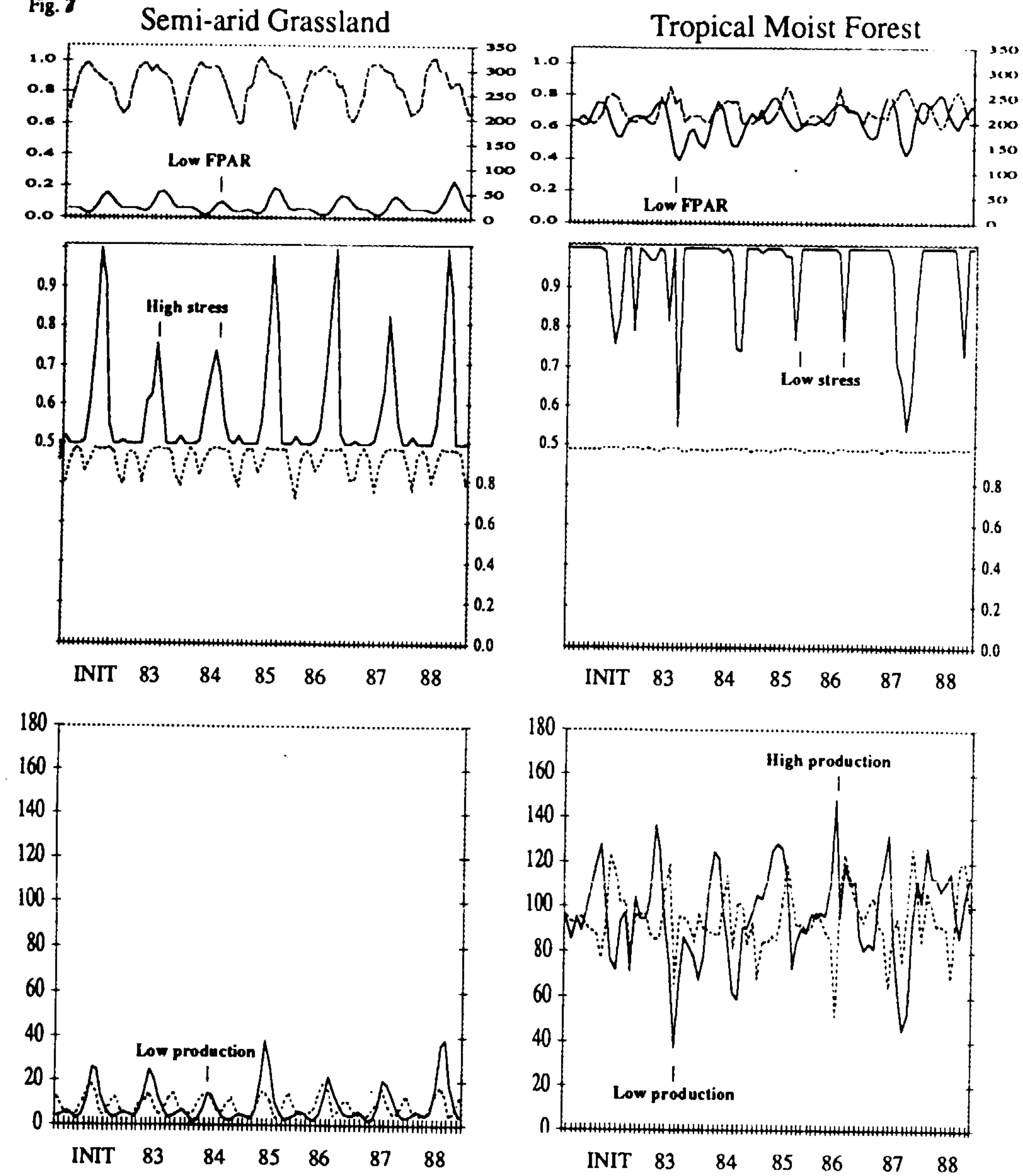
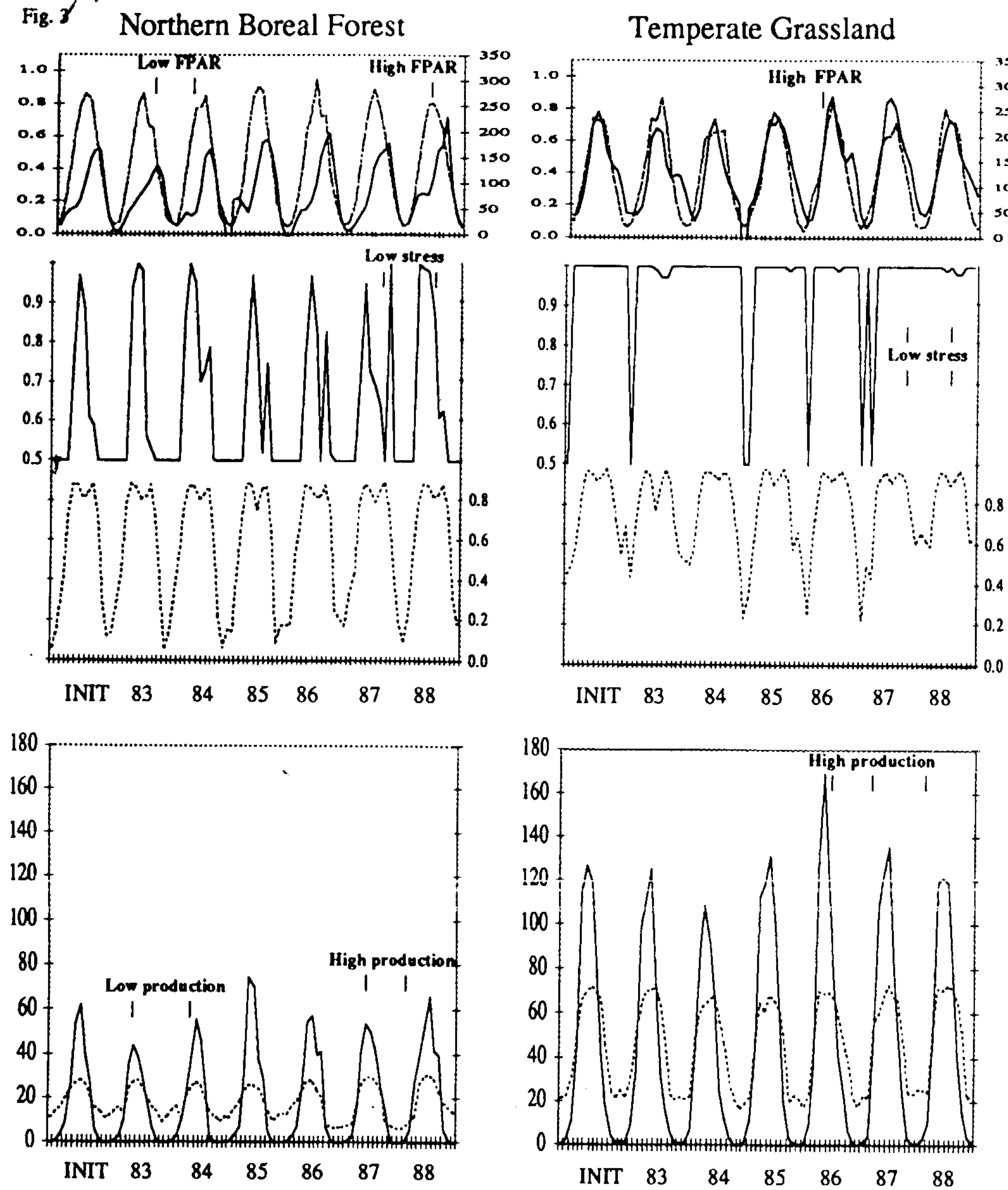

Semi-arid Grassland
Tropical Moist Forest
Low FPAR
High stress
Low stress
Low production
High production
INIT 83 84 85 86 87 88

Fig. ~~3~~ 4


Northern Boreal Forest
Temperate Grassland
Low FPAR
High FPAR
Low stress
Low production
High production
INIT
83
84
85
86
87
88